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Dijet Searches for Supersymmetry at the LHC

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We present several strategies for searching for supersymmetry in dijet channels that do not explicitly invoke missing energy. Preliminary investigations suggest that signal-to-background ratios of at least 4–5 should be achievable at the LHC, with discovery possible for squarks as heavy as ~ 1.7 TeV.

I. INTRODUCTION

The LHC is set to explore the physics of the weak scale, whatever it should turn out to be. Supersymmetry is one of the leading candidates and enormous effort has been dedicated to studying missing energy signals that characterize almost any weak-scale supersymmetric model. However, supersymmetry searches will be challenging and disentangling the supersymmetry parameters will be more difficult still.

In light of the above, it is imperative to study every possible channel in order to optimize our chances of discovering new physics and understanding the underlying theory. In this regard, events with the lowest multiplicity may be the simplest ones with which to make headway on the inverse problem.

Although two-jet events with missing energy have been studied at the Tevatron [1], they have been less prominent in LHC studies. ATLAS has shown that two jet events can be useful for certain SUSY models, both for discovery and for constraining superpartner masses [2], but recent ATLAS and CMS studies have focused more heavily on the more challenging cascade decays. In this paper we study one novel and two existing kinematic variables that can be used to capture dijet missing-energy events without explicit reference to missing transverse energy. We find that pairs of these variables can be used to give signal-to-background of at least 4–5, indicating that these variables are worth exploring with a full detector simulation¹.

Dijet events are worthy of attention as a potentially clear window into parameter space. They are not results of complicated cascade decays but arise simply from two squarks decaying to two quarks and two neutralinos. Because we know the identity of the particles involved and because there are so few, the signal is relatively straightforward to interpret. For example, with sufficient integrated luminosity, these events alone can be used to constrain the squark and neutralino masses. Dijet studies along the lines explored here may usefully supplement

recent analyses dedicated to distinguishing SUSY from other models using events with at least three jets [5].

The kinematic variables we consider are constructed from the two jets' momenta alone. These variables should have different systematic uncertainties than missing transverse energy since they pick out slightly different events and are based on different measurements. At the very least, then, the searches we suggest should be worthwhile as cross-checks of standard searches. The variables we use may also be useful for optimization when signal-to-background is relatively low.

The searches we describe will be most effective when squarks are pair-produced in abundance and have large branching ratios to decay directly to the lightest neutralino, which requires that squarks are lighter than the gluino so that cascade decays through gluinos are absent. Because t -channel gluino exchange is an important source of squark pair production, the lighter the gluino the more prominent the signal. For the parameter points considered below, we find the signal is cut by a factor of $\sim 6 - 7$ when the gluino decouples. Fortunately, comparable gluino and squark masses are a feature of a large class of models – most notably high-scale models where the heavier gluino mass feeds into the squark mass. We focus on such models in this study.

II. ANALYSIS DETAILS

Before getting to the dijet properties that will be the focus of our study, we consider the effectiveness of \cancel{E}_T and \cancel{H}_T , the missing transverse energy obtained from the dijet system alone. After requiring the sum of the two jets' p_T 's to be greater than 500 GeV, event rates and signal-to-background ratios for one particular SUSY point are presented in Table I (details regarding event generation and cuts are given below). Neither variable suffices for a clean search, but we observe that the S/B values obtained using \cancel{H}_T are essentially identical to those obtained using \cancel{E}_T . This analysis suggests that, in the two-jet channel at high p_T , nothing is to be gained by using full \cancel{E}_T rather than kinematic variables associated with the two jets alone.

We now present three dijet variables that can be used to separate signal and background, with $\sim 1\%$ of signal

¹ Such a study has been started by CMS [3]. In addition, ATLAS is currently engaged in an updated dijet study [4].

	$E_T/\#T$ cut	300	350	400	450	500	550	600	650	700
E_T	σ_{susy} (fb)	864.	759.	645.	526.	397.	257.	143.	81.9	51.1
	S/B	0.7	1.0	1.3	1.7	1.8	2.0	1.8	1.5	1.4
$\#T$	σ_{susy} (fb)	862.	757.	639.	521.	379.	229.	128.	74.5	47.4
	S/B	0.7	1.0	1.3	1.7	1.9	1.8	1.7	1.5	1.3

TABLE I: For dijet events passing the cuts described in the text, the dependence of the signal cross section and signal-to-background (S/B) on a variable E_T cut (top), and on a variable $\#T$ cut (bottom). All energies are in GeV.

events passing all cuts.

- α : which we define as the ratio of the p_T of the second hardest jet and the invariant mass formed from the two hardest jets,

$$\alpha \equiv \frac{p_{T2}}{m_{jj}}. \quad (1)$$

As far as we know, this variable has not been considered previously. Background events generally trail off at $\alpha = 0.5$, whereas supersymmetry events with invisible decay products can easily have larger α . Large α tends to arise in events in which the jets are not back-to-back. As one extreme example, if the two jets are nearly aligned, their invariant mass can be quite small, leading to very large α .

Because of the background's sharp drop-off around $\alpha = 0.5$, this variable is potentially useful as a diagnostic tool for analyzing two jet events and cleanly separating signal events from QCD.

- $\Delta\phi$: the azimuthal angle between the two hardest jets. Azimuthal angle is often used in conjunction with missing transverse energy, and $\Delta\phi$ was among the variables used in the dijet SUSY search at D0 [1].
- M_{T2} [14]: which is defined for events in which two particles of the same mass undergo identical semi-invisible decays, as

$$M_{T2}(\chi) = \min_{\not{q}_1 + \not{q}_2 = \not{p}_T} \{ \max[m_T(p_1, \not{q}_1, \chi), m_T(p_2, \not{q}_2, \chi)] \}, \quad (2)$$

where p_1 and p_2 are the momenta of the visible particles, \not{p}_T is the missing transverse momentum of the event, and m_T is the transverse mass function, which depends on an assumed value χ of the invisible particle's mass. In calculating $M_{T2}(\chi)$ we use the missing transverse momentum as determined by the dijet system alone.

If χ is taken to be equal to the mass of the invisible particle, the M_{T2} distribution will have an endpoint at the mass of the decaying particle. Not knowing this mass, M_{T2} endpoints still constrain the masses of the decaying and invisible particles, as emphasized in [14] and used below.

We consider these variables singly and in tandem. We find the first two variables are useful in that one can choose parameter-independent cuts that give sizable S/B , whereas the last variable, though more parameter-dependent in its optimization, might ultimately maximize S/B . Since the advantage is not overwhelming, we expect all the variables could prove useful, either at the trigger or analysis level. Because they are dimensionless, the first two variables might have the further advantage of being less sensitive to absolute energy scale, and might therefore have lower systematic errors.

For all our analyses, we select events in which exactly two jets have $p_T > 50$ GeV, with no isolated leptons, photons, or τ jets. One could attempt to achieve better background rejection by an additional veto on extra jets with lower p_T . In general, we have chosen felicitous cuts but have not pursued a careful optimization, which will be more appropriate at the full-detector-simulation level.

A gluino that is only slightly heavier than the squarks arises naturally in models with supersymmetry broken at a high scale, as renormalization-group effects prevent the squarks from being hierarchically lighter than the gluino. For our analyses we specify parameters at the high scale and use the SUSY-HIT package [6] to calculate superpartner masses and decay branching ratios. In the relevant parameter regions, the signal depends strongly on $M_{1/2}$, the unified gaugino mass at the high scale, and is less sensitive to M_0 , the unified scalar mass, because the squark mass is dominated by gauge-loop contributions. We set the other SUSY parameters to be $\tan\beta = 10$, $A_0 = 0$, and $\mu > 0$.

The backgrounds included in our analyses are QCD, $(W \rightarrow l\bar{\nu})/(Z \rightarrow \nu\bar{\nu})$ +jets, and $t\bar{t}$. We have checked that diboson+jets production does not significantly modify our results. The QCD and $t\bar{t}$ samples were generated with Pythia 6.4 [7], and Z/W +jets with Alpgen 2.12 [8]. Fully showered and hadronized events were then passed to the PGS 4.0 detector simulator [9], with the energy smearing in the hadronic calorimeter given by $\Delta E/E = 0.8/\sqrt{E/\text{GeV}}$ and the calorimeter granularity set to $(\Delta\phi \times \Delta\eta) = (0.1 \times 0.1)$. Jets were defined using a cone algorithm with $\Delta R = 0.4$.

A K -factor of 2 is applied to the QCD sample, but no K -factor is used for W/Z production, because the most important contributions come from W/Z +2 jets, which are not enhanced at NLO [10]. (After cuts, W/Z production ends up being the dominant background to SUSY dijet events, so to include a K -factor one can simply divide our signal-to-background ratios by K .) For $t\bar{t}$ we use $\sigma = 830$ pb as the NLO production cross section [11]. Including the K factors our samples sizes are $\sim 0.8 \text{ fb}^{-1}$ for QCD, $\sim 20 \text{ fb}^{-1}$ for $t\bar{t}$, and $\sim 100 \text{ fb}^{-1}$ for W/Z . Appropriate generator-level kinematic cuts were imposed to obtain the QCD and W/Z samples.

SUSY samples were also generated with Pythia. For each parameter point we use Prospino 2.0 [12] to calculate an appropriate K -factor from the NLO cross section for squark pair production [13].

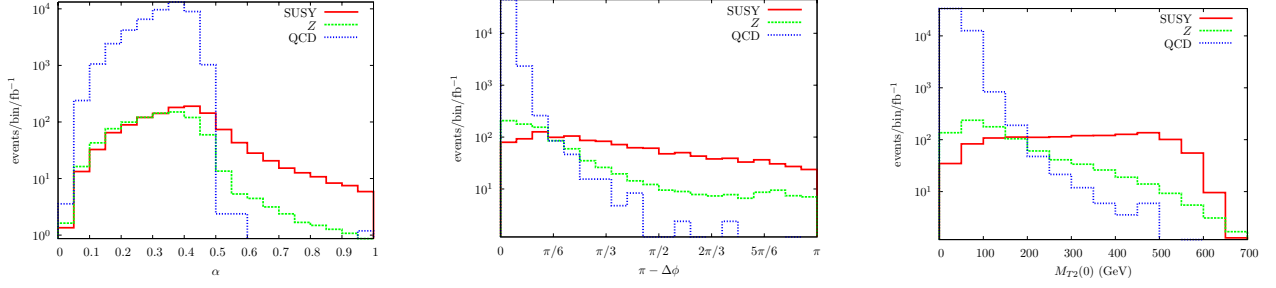


FIG. 1: SUSY, $Z \rightarrow \nu\bar{\nu}$ +jets and QCD rates for passing the cuts described in the text, as functions of α (left), $\Delta\phi$ (middle), and $M_{T2}(0)$ (right).

III. RESULTS

The plots in Figure 1 suggest that appropriate cuts on α , $\Delta\phi$, and/or M_{T2} can suppress both the QCD background and the dominant background after cuts, ($Z \rightarrow \nu\bar{\nu}$)+jets. The SUSY parameter point used here is $(M_{1/2}, M_0) = (300, 100)$ GeV, and we impose a hard cut on the sum of the two hard jets' transverse momenta,

$$p_{T1} + p_{T2} > 500 \text{ GeV}. \quad (3)$$

To streamline the analysis, events were required to have $\cancel{E}_T > 100$ GeV for Figure 1 and at least one of $\alpha > 0.5$, $\Delta\phi < 2\pi/3$, and $\cancel{E}_T > 100$ GeV for Figure 2. Removing these requirements does not affect the results once optimal cuts on α , $\Delta\phi$, and/or M_{T2} are made.

Evidently signal dominates over background for $\alpha \gtrsim 0.5$, $\Delta\phi \lesssim 2\pi/3$, and $M_{T2} \gtrsim 300$ GeV. We will soon see that α , $\Delta\phi$, and M_{T2} can be used to discriminate signal from background by themselves, but first we point out that cuts on these variables can improve an analysis based on \cancel{E}_T or \cancel{H}_T . For example, the combination ($\alpha > 0.45$, $\cancel{H}_T > 300$ GeV) selects 315 signal events per fb^{-1} , with $S/B = 4.3$. The combination ($\Delta\phi < 2\pi/3$, $\cancel{H}_T > 450$ GeV) gives a somewhat lower S/B (3.1), but with more events (429). An M_{T2} cut of 450 GeV gives the largest S/B of all (5.0, with 304 events), and in fact there appears to be no benefit in supplementing the M_{T2} cut with the \cancel{H}_T cut.

Figure 2 suggests that each of α , $\Delta\phi$, and M_{T2} can be used independently to observe a clear signal, without employing \cancel{H}_T at all. Well-chosen cuts give \sim a few $\times 10^2$ signal events after 1 fb^{-1} , with $S/B \sim 3 - 5$.

Figure 2 also shows how the three variables can be used in pairs to improve S/B in conjunction with the signal event-rate. We again find that M_{T2} seems to dominate a little, but since we do not know if this is the cleanest variable to use in practice, which can be determined only after a full detector simulation, we present all combinations. Any two on their own can potentially give a robust signal.

As an example, we consider the combination $\Delta\phi < 2\pi/3$ and $\alpha < 0.45$, which gives a good S/B and a decent event rate. As stated earlier, we do not optimize cuts, but we use this combination that works rather well.

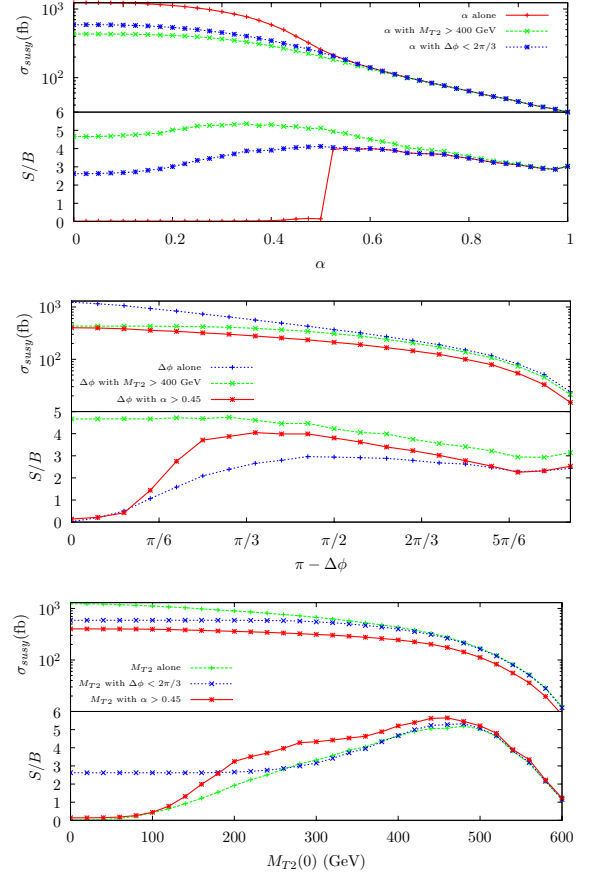


FIG. 2: For events preselected as described in the text, the dependence of the signal cross section and S/B on a variable α cut (top), a variable $\Delta\phi$ cut (middle), and a variable M_{T2} cut (bottom).

With those cuts in place, Figure 3 shows signal and background events binned in the sum of the two hardest jets' transverse momenta. We see that Z +jets is the dominant background, followed by W +jets. A total of four QCD events with $p_{1T} + p_{2T} < 500$ GeV passed the cuts, out of a sample corresponding to over 1.5 fb^{-1} of integrated luminosity, divided by the K factor. A higher luminosity sample would be needed to get a better esti-

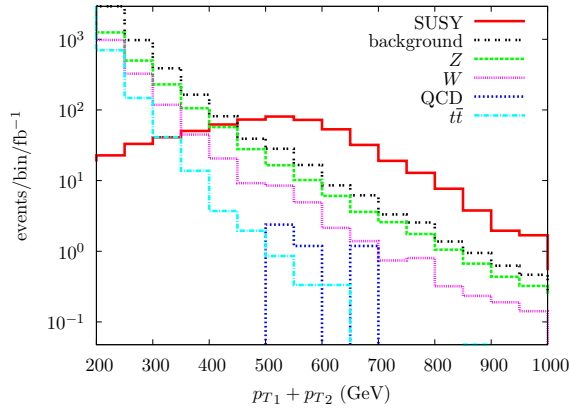


FIG. 3: Signal and background rates after the cuts $\Delta\phi < 2\pi/3$ and $\alpha > 0.45$. The QCD background is not included for $p_{1T} + p_{2T} < 500$ GeV. We take $(M_{1/2}, M_0) = (300, 100)$ GeV.

	$N_{jets} = 2$	$p_{T1} + p_{T2} > 550$	$\Delta\phi < 2\pi/3$	$\alpha > 0.45$
ϵ	1.08×10^{-1}	5.04×10^{-2}	2.05×10^{-2}	9.48×10^{-3}
σ_{susy} (fb)	2.33×10^3	1.09×10^3	443.	205.

TABLE II: The efficiencies ϵ for signal events to pass the successive cuts, taking $(M_{1/2}, M_0) = (300, 100)$ GeV.

mate of the QCD background, but it seems safe to say that the W and Z backgrounds are more important.

In Figure 3 we see that S/B is cleanest at high p_T . Of course the optimal p_T cut depends on underlying parameters that are not known *a priori*, but a scan at high p_T should help maximize S/B . For the chosen parameter point, cutting above $p_{1T} + p_{2T} = 550$ GeV gives $S/B = 4.9$, with an average of 205 signal events after 1 fb^{-1} . Table II shows the efficiencies with which the SUSY events pass the successive jet multiplicity, $p_{T1} + p_{T2}$, $\Delta\phi$, and α cuts.

The final efficiency is lower than that for SUSY searches with additional jets, and so despite the different systematics SUSY might well be discovered in other channels first. Moreover, the dijet channel is relevant only for certain models. On the other hand, this analysis picks out particularly simple events—two squarks decay to produce two jets and two neutralinos. If these events do occur it would certainly be worthwhile to study them in isolation.

For example, with enough luminosity these events alone can be used to obtain a simple constraint on the squark and neutralino masses, using the M_{T2} event function [14] introduced above. If one can ignore all visible particles in the event except those in the two jets, one expects the endpoint

$$M_{T2}(0)_{max} = \frac{m_{\tilde{q}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{q}}}. \quad (4)$$

For the parameter point under study, the predicted end-

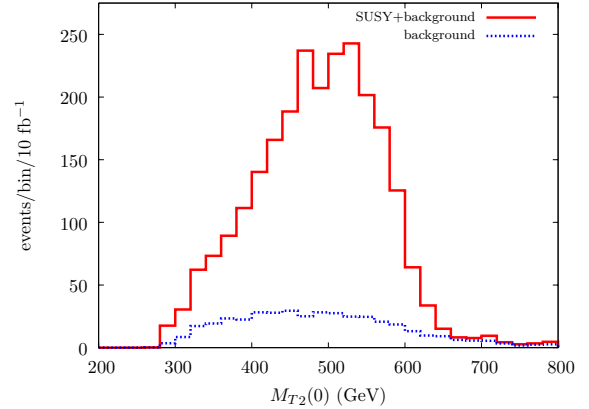


FIG. 4: The m_{T2} distribution for signal and background, after the cuts described in the text. We take $(M_{1/2}, M_0) = (300, 100)$ GeV.

point turns out to be 619 GeV if we use the mass of the right-handed squarks, which are the ones that decay predominantly to $\tilde{\chi}_1^0 q$. Figure 4 shows the $m_{T2}(0)$ distribution for $10/\text{fb}$ of data, with the cuts of Table II imposed. A sharp drop-off leading up to ~ 620 GeV is evident, consistent with expectations. The spill-over to larger values is mostly due to the effects of extra jets not included in the calculation of the missing transverse energy (in calculating $M_{T2}(0)$ we use the missing transverse momentum as determined by the dijet system alone).

The $(\alpha, \Delta\phi)$ analysis we have described can be effective for higher-mass searches as well, with the cut on the sum of the two jets' transverse momenta increased appropriately. Table III gives results for other parameter points, with the cuts on $p_{1T} + p_{2T}$ again chosen to give robust values of S/B . The M_0 values are chosen to be near the lower bounds below which a stau LSP results. Provided that the squarks remain lighter than the gluino, increasing M_0 lowers the event rate somewhat but not dramatically. For $(M_{1/2}, M_0) = (300, 300)$ GeV, for example, the same cuts used for the $(M_{1/2}, M_0) = (300, 100)$ GeV point give 195 events after 1 fb^{-1} , with $S/B = 4.7$.

Taking $S/\sqrt{B} > 5$ as the relevant criterion, our results suggest that discovery through the dijet channel should be possible for squark masses up to about ~ 1700 GeV after 100 fb^{-1} of integrated luminosity. By the same measure, discovery for lighter squark masses, ~ 600 GeV, should be possible after $\sim \text{a few} \times 10^2 \text{ pb}^{-1}$ or less. It may be optimistic to focus on S/\sqrt{B} as a discovery criterion, as doing so assumes that the background is fully understood. However, it is worth pointing out that (1) events with leptonic Z decays will provide some experimental handle on the dominant background, Z +jets, and (2) the shapes of the $p_{T1} + p_{T2}$ distributions for signal and background events passing the α and $\Delta\phi$ cuts are quite different (see Figure 3). The excesses obtained in our analysis would lead to a prominent bump in the measured distribution, which would not be accommodated simply by rescaling

$(M_{1/2}, M_0)$	$(m_{\tilde{g}}, m_{\tilde{q}_R})$	$\sum p_T$ cut	ϵ	σ_{susy} (fb)	S/B
(300, 100)	(716, 640)	550	9.5×10^{-3}	205.	4.9
(450, 100)	(1040, 918)	800	7.9×10^{-3}	21.3	4.7
(600, 150)	(1358, 1195)	1050	8.1×10^{-3}	4.07	5.0
(750, 200)	(1669, 1465)	1250	9.6×10^{-3}	1.17	4.8
(900, 200)	(1965, 1726)	1450	1.0×10^{-2}	0.37	3.5

TABLE III: Efficiencies, event rates, and signal-to-background ratios for various SUSY parameters, using the cuts described in the text. All masses are in GeV.

the background.

IV. CONCLUSIONS

We have studied several kinematic variables that can be used for dijet SUSY searches, and found that they

give reasonable signal-to-background ratios. Dijet events can be used to constrain SUSY mass parameters should the type of supersymmetry model we have considered be correct. Studies of Z +jet events with leptonic Z decays will give a better understanding of the background and a more reliable extraction of signal from background. For the future, it would be useful to see how well the lessons here can be applied to develop multijet searches that do not rely on full missing energy.

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